EVALUATION OF CAPTURED WATER COLUMN TECHNOLOGY FOR ADVANCED ULTRASONIC SIZING TECHNIQUES

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INTRODUCTION

Ultrasonic (UT) inspection of aircraft engine parts has traditionally been conducted in an immersion water tank. However, experience has shown that the immersion tank is usually large, awkward, and tedious to work with. An alternative method which does not require immersion would increase the time efficiency of the UT inspection. One such method would be to use a captured water column coupling system, which closely approximates the immersion method and eliminates the need for a large immersion tank. The tank would be replaced by a trough or water collection tray to collect the water produced by the low water flow of the captured water column.

During the early stages of the U.S. Air Force Retirement for Cause (RFC)* program, a need for such a system was recognized. Some of the major requirements defined for the captured water column were the following. It had to:

(1) Have a small noise factor so that defects on the order of 0.02 inch could be detected.

(2) Produce ultrasonic data comparable to that obtained with immersion systems.

(3) Have minimal effect on the amplitude and frequency content of the ultrasonic signal so that detection and sizing methods could work.

(4) Fit inside the bore of the F-100 engine disk and be compatible as much as possible with upcoming advanced ultrasonic inspection methodology.

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These requirements and the efforts aimed at satisfying these needs have led to the ultrasonic captured water column (or bubbler) described in this paper.

DESIGN PARAMETERS

The bubbler consists of a bubbler housing, internal water flow vanes, and a nozzle. Water enters through two inlets and is directed evenly through the bubbler housing by the flow vanes. The housing is designed to fit around a modified 10 MHz, 3/8 inch diameter transducer. The housing also has a flow directing end that directs the water into the face of the focused transducer, thus preventing an air gap at the transducer face. The housing can be easily diassembled to replace the transducer, and the nozzle is screwed onto the end of the bubbler housing. The bubbler nozzle is made of a silicon cone inserted into an epoxy shell. The nozzle orifice is 7/16 inch in diameter.

The design utilizes a closed loop water supply which is filtered prior to entering the nozzle. This greatly reduces the formation of small air bubbles in the water stream which could generate random noise. This bubbler design has been studied and carefully evaluated to determine how the ultrasonic data taken in the captured water column (CWC) mode compares to that taken in the immersion mode in terms of reflected ultrasonic amplitude and signal frequency content. In addition, artificial defects contained in real geometry parts have been used to evaluate the detection capabilities of the RFC inspection system utilizing the bubbler concept.

DISCUSSION OF EVALUATION TESTS

The emphasis of the initial test plan developed for the captured water column was to determine the suitability of the CWC for use in the RFC/NDE ultrasonic test module. Two areas of concern were near-surface flaw resolution and the effect of the CWC on the advanced ultrasonic sizing techniques. The test plan called for data to be taken under identical circumstances with the transducers in the immersion mode and the CWC mode so that a direct comparison of the CWC effects could be made.

During initial tests, data were collected on seven test specimens. Test block RFC-SwRI-UT-01 was designed to test near-surface flaw detection. The centers of the 0.5 mm diameter side-drilled holes were placed at 0.6, 1.0, 1.4, and 1.8 mm from the top surface. Test blocks RFC-SwRI-UT-02, SwRI 97516, Rockwell 48-2-8-84, and Rockwell 51-3-4-64 were designed to test detection sensitivity to small flaws. The flat-bottom, end-milled holes in block RFC-SwRI-UT-02 were 0.5 mm in diameter and oriented at a 45 degree angle.

SwRI block 97516 contained diffusion bonded spherical voids with diameters of 0.5 and 1.0 mm approximately 19.1 mm below the surface. Rockwell block 51-3-4-64 contained diffusion bonded voids 0.4 and 0.8 mm in diameter 12.7 mm below the surface. GE block CC-2D-2DH contained side-drilled holes 0.8 mm in diameter below surfaces with various radii of curvature, and GE block CC-2D-FBH contained similar diameter flat bottom holes. The GE and SwRI-UT blocks were aluminum, the SwRI 97516 block was IN 100, and the Rockwell blocks were titanium.

The tests were conducted over a wide range of angles from 0 degrees longitudinal to 70 degrees shear for both the immersion (IMM) mode and the captured water column mode. The test equipment consisted of a Panametrics 5055PR pulser/receiver, a Tektronix 7854 waveform sampler and digitizer, a Hewlett-Packard 9826 desk top calculator, and the ultrasonic manipulator required with either the CWC or IMM mode.

The following parameters were evaluated for the two modes:

(1) The RF waveform peak amplitude difference between the IMM and CWC modes.

(2) The power spectrum for each mode for a given reflector.

(3) Size estimates given by each advanced technique.

The judgment criteria used to evaluate the comparison were as follows:

(1) The amplitudes of the two modes were to be within 3 dB.

(2) The difference power spectrum between the two modes was not to exhibit a deviation greater than 0.5 at any frequency.

(3) The two modes must give size estimates within 20 percent of each other for each defect inspected.

Subsequent data were collected on an F-100 engine 8th disk which contained several side-drilled holes with diameters of 0.010 inch and 0.20 inch located at different locations in the bore (as schematically shown in Figure 1). The depth of the holes ranged from approximately 0.02 inch to 1.0 inch below the surface. Data were also collected on the internal crack specimen shown in Figure 2. The RFC ultrasonic inspection system was used to collect data. The ultrasonic instrument used in the system is the SRL 1712A digital ultrasonic instrument.

RESULTS

Detection

During the initial testing, approximately 250 sets of immersion versus captured water column data were taken. The amplitudes of the CWC and IMM modes were usually within 3 dB. The average difference between the CWC and IMM modes was +0.7 dB with a standard deviation of 3 dB. The major cause of variation was believed to be accumulation of bubbles on the transducer face for both immersion and bubbler modes during the test.

Time amplitude (A-scan) and power spectra for all data sets showed that there was very little difference between the two modes. A special set of data was taken for the purpose of carefully analyzing the effects on frequency in the CWC mode versus those in the IMM mode. This set of data was analyzed for amplitude variation and for applicability to the satellite pulse and Born inversion sizing techniques. The results showed that for moderate gain levels (30 dB), the general wave shapes and amplitudes are nearly identical. For high gain levels (50 dB), the amplitudes are within 3 dB, but the captured water column A-scan has low frequency noise not present in the immersion mode. (Filtering the inlet water to the CWC was later shown to greatly reduce the noise.)

Sizing

The effects of the CWC on the satellite pulse and Born inversion sizing techniques were evaluated.

The satellite pulse technique was not adversely affected by the CWC low frequency noise at the high gain levels, but the Born inversion technique was. Low frequency data below 2 MHz is very important in estimation

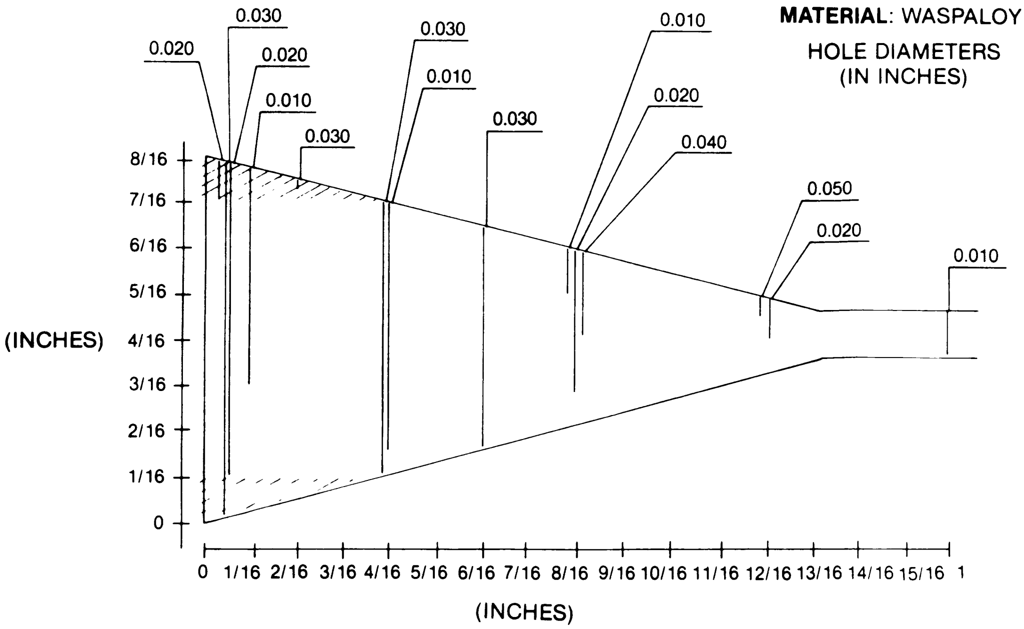

Fig. 1. Side-drilled holes in the 8 HPC disk bore

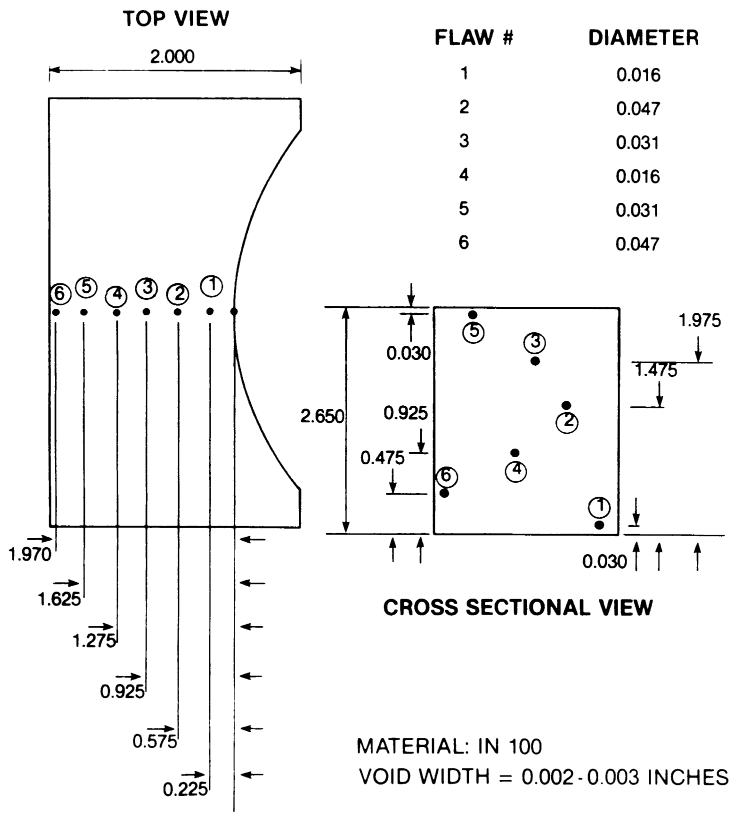

Fig. 2. Internal flaw specimen containing mal-oriented, penny-shaped voids

of the flaw center, and is necessary for the Born technique to work properly. Thus, the prototype CWC required improvements, or optimization, to be utilized with the Born inversion technique.

In order for the Born inversion technique to work properly, the following relationship between frequency and approximate flaw size range must be satisfied:

$$0.5 \leq \frac{2\ af}{V} \leq 2.5 \tag{1}$$

where a is the approximate flaw size range (radius), f is the transducer frequency, and V is the velocity of sound in the material. Based upon the frequency requirements to size flaws with radii in the range from 0.3 to 0.8 mm using the Born inversion technique, it is important that the frequency response of the CWC system be uncorrupted above 0.6 MHz. Therefore, the aperture of the CWC tip must be larger than the beam diameter of the lowest frequency of interest.

The diameter of the beam (2b) at a focus of f_L is given by

$$2b = \frac{f_L \lambda}{D} \tag{2}$$

where D is the diameter of the transducer and λ is the ultrasonic wavelength.

To optimize the CWC nozzle for a 3/8-inch diameter transducer with a 3-inch focus in water for use with the Born inversion method, the nozzle aperture must be approximately 1/2 inch. However, it was difficult to maintain consistent water flow with this aperture size. The maximum aperture size that produced consistent flow was experimentally found to be 7/16 inch.

The final design of the bubbler nozzle provides for a 7/16 inch diameter orifice. Based upon the analysis above, this nozzle will successfully pass frequencies above 1.06 MHz. (The optimized CWC was not evaluated using the Born inverstion sizing technique.)

The second set of tests were designed to evaluate the flaw detection capabilities of the optimized CWC system. These data were taken with the RFC ultrasonic inspection system from specimens shown in Figures 1 and 2. The water flow rate was 0.7 gallons per minute during the tests.

Figure 3 shows oscilloscope traces of the ultrasonic signal taken from a 0.020-inch side-drilled hole defect 0.03 inch below the surface. Figure 3a is the A-scan over a 15 μsec window, Figure 3b is the same signal expanded to cover a 3 μsec window, and Figure 3c is the frequency spectrum of the A-scan signal. The data were from a combination of four time-averaged signals. The data illustrate that there is no bad effect on the detection of these types of defect signals. Notice the satellite pulse following the main reflection signal. (The 1712A receiver has a filter with cutoffs below 3 MHz and above 12 MHz.)

Figure 4 shows the data taken from a 0.020-inch diameter side-drilled hole located 0.5 inch below the surface of the waspaloy disk. Again notice the presence of the satellite pulse.

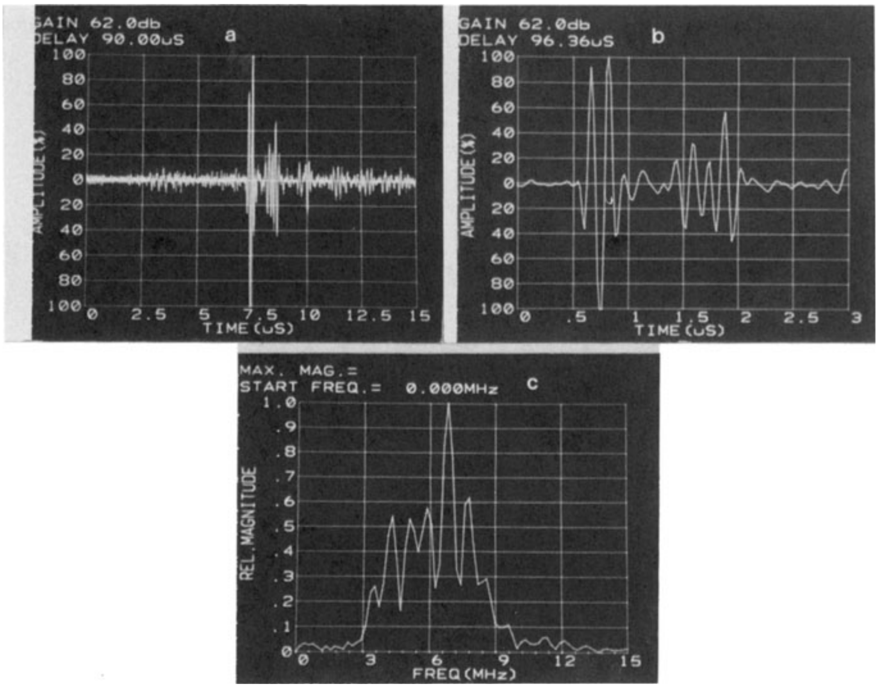

Fig. 3. Data from 0.020-inch diameter side-drilled hole located near the surface of 8th HPC disk

Figure 5 shows the data from a 0.010-inch diameter hole 0.06 inch below the surface and Figure 6 shows the data taken from a 0.010 inch diameter side-drilled hole that is 1.0 inch below the surface. The satellite pulse can be seen in Figure 5, but not in Figure 6. These data clearly indicate that the waspaloy has a tremendous attenuation effect (approximately 20 dB/inch one way) as well as a filtering effect. (Note that the near-surface peak frequency is approximately 7 MHz, while the peak frequency for the defect that is 1 inch deep is approximately 3.5 MHz. Thus, the material acts as a frequency filter.)

Figure 7 shows data taken from a simulated buried crack. This defect is a maloriented half-penny shaped void which is 0.047 inch in diameter and located 1.975 inches from the surface. This defect is easily detected.

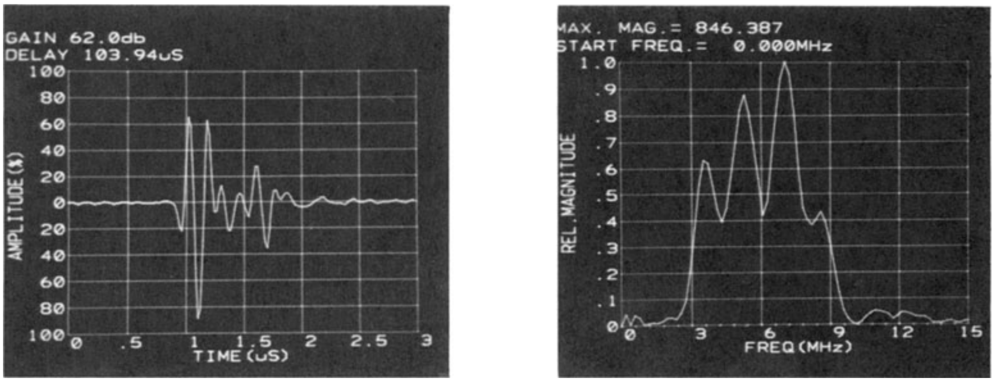

Fig. 4. Data from 0.020-inch diameter side-drilled hole at a depth of 0.5 inch on 8th HPC disk

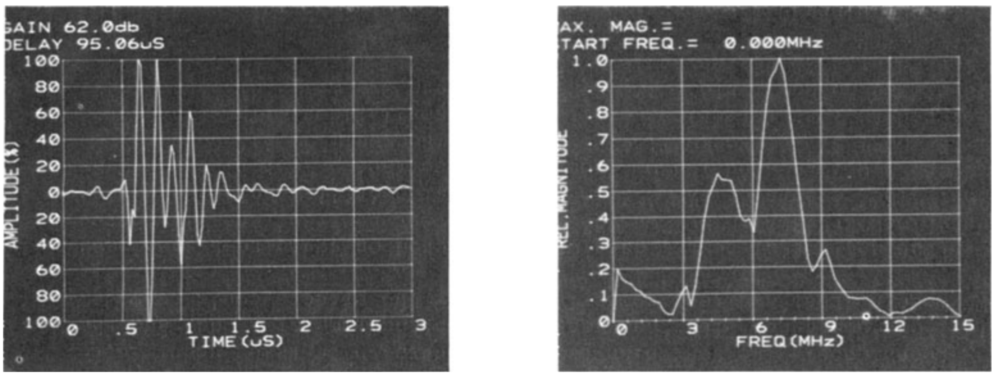

Fig. 5. Data from 0.010-inch diameter side-drilled hole at a depth of 0.06 inch on 8th HPC disk

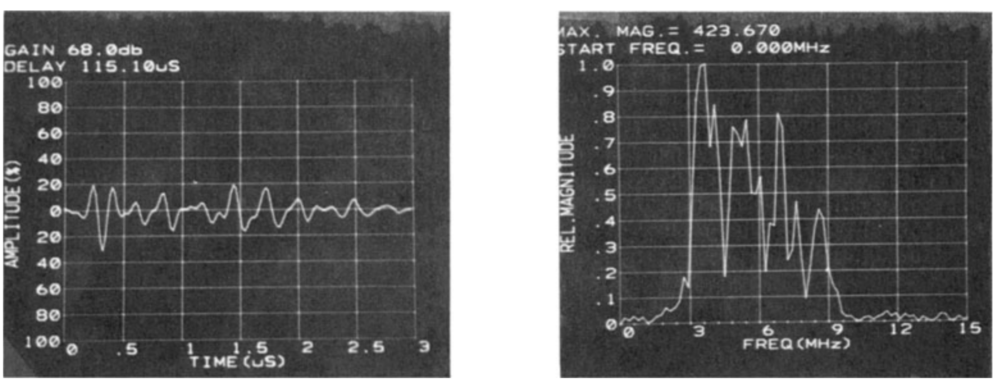

Fig. 6. Data from 0.010-inch diameter side-drilled hole at a depth of 1.0 inch on 8th HPC disk

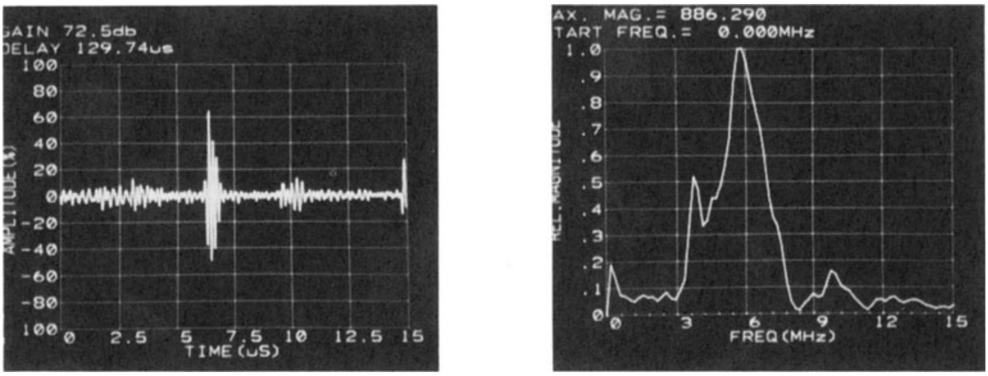

Fig. 7. Data from a 0.047-inch diameter penny-shaped void at a depth of 1.975 inches (composite of 16 averages)

CONCLUSIONS

The ultrasonic data collected using the captured water column technology has shown that the defect detection capability of the RFC is comparable to an immersion system. In addition, this technology does not appear to eliminate the use of advanced sizing techniques such as the satellite pulse and Born inversion, although more testing is needed to verify this. Furthermore, the captured water column technology has several logistical advantages over the use of immersion systems for the RFC program including similar UT and ET mechanical systems and ease of operation.